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Effect of the concentration and stirring up on the settleability parameters for activated sludge samples.

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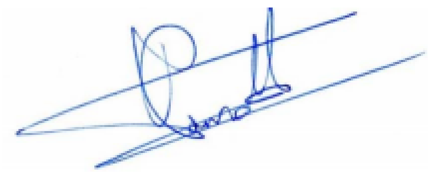

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ABSTRACT

Water is an essential resource for life and requires the best possible quality for human health and welfare. Water is also essential for our eco-systems as it provides a natural habitat for many plant and animal species. However, water resources are under increasing pressure in many parts of the world due to the continuously rising demand for clean water and the production of large amounts of wastewater. In this respect, the main objective of the wastewater treatment plant is to remove the maximum pollutants from the water and obtain high quality water in the effluent. For that reason, a good functioning and cost-effective wastewater treatment system is of crucial importance in order to prevent further pollution and depletion of water resources.

For obtaining a clear effluent, the secondary treatment done in the secondary settling tanks is a crucial step. The separation of the activated sludge from the clear water is generally done by gravitational settling of spontaneously formed flocs of activated sludge. The problem is when flocs with poor settling properties are plentiful, causing in that way a loss of the activated sludge into the effluent. The efficiency of the settling process is dependent on both physical (design and operation of the settlers, turbulence in the aeration, etc.) and chemical/biological factors (wastewater composition) and this makes the process very complex. For that reason, the secondary settling tank and the bioreactors have to be an interacting system.

The problem is that an expansion of the settlers is not always possible due to limited space available as well as limited funds and it is therefore necessary that the existing settlers work efficiently. Moreover, the operation and control of the secondary settler tank is also an important performance-limiting factor in conventional waste water treatment plants. Due to this limits, it is important to know which factors affect the settling process of activated sludge to be able to operate the wastewater plant in such a way that sludge with good settling properties is produced.

Although a considerable amount of research has been done within this field, the factors affecting the settling properties of activated sludge are not fully understood. In order to improve existing models, the behavior of the activated sludge needs to be more understood.

Therefore, this final project aims to apply experiments already done with primary effluent sample to activated sludge samples. Furthermore, the project aims to improve the existing experiments for a better understanding of the settling behavior of the activated sludge.

Key words: Waste Water Treatment Plant (WWTP), Secondary treatment, Bioreactors, Secondary Settling Tanks (SST), Activated Sludge (AS), Settling properties.

RESUM

L’aigua és un recurs imprescindible per a la vida i requereix de la millor qualitat sanitària possible per al consum humà i el benestar. L'aigua és també essencial per als nostres ecosistemes, ja que proporciona un hàbitat natural per a moltes espècies de plantes i animals. No obstant això, els recursos hídrics estan sota una pressió creixent en moltes parts del món a causa de la contínua demanda creixent d'aigua neta i la producció de grans quantitats d'aigües residuals. Referent a això, l'objectiu principal de la planta de tractament d'aigües residuals és eliminar al màxim els contaminants de l'aigua i obtenir un efluent de qualitat. Per aquesta raó, un bon funcionament i un bon rendiment d’una planta de tractament d'aigües residuals és de crucial importància per tal d'evitar una major contaminació i l'esgotament dels recursos hídrics.

Per a l'obtenció d'un efluent amb la mínima quantitat de contaminants, el tractament secundari dut a terme als tancs de sedimentació secundària, és un pas crucial. La separació dels fangs actius de l'aigua es produeix principalment gràcies a la sedimentació gravitacional dels flocs que es formen espontàniament. El problema es troba quan els flocs no presenten bones propietats de sedimentació, causant la presència de fangs actius en l’efluent. L'eficiència del procés de sedimentació depèn de factors físics (disseny i operació dels sedimentadors, la turbulència provocada per l’aeració, etc.) i factors químics / biològics (composició de les aigües residuals) i això fa que el procés sigui molt complex. Per aquesta raó, els bioreactors i els tancs de sedimentació secundària es tracten com un sistema interactiu, ja que un depèn de l’altre.

El problema és que una modificació dels tancs de sedimentació no és sempre possible a causa de l’espai limitat disponible, així com dels fons econòmics i per tant cal que els tancs existents funcionin de manera eficient. A més a més, l'operació i el control també són factors limitadors importants en plantes d’aigües residuals convencionals. A causa d’aquests límits, és important saber quins factors afecten al procés de sedimentació dels fangs actius per poder-los controlar i crear fangs amb bones propietats sedimentaries.

Malgrat la quantitat de recerca invertida en aquest camp, els factors que afecten a les propietats de sedimentació dels fangs actius no s'acaben d’entendre completament. Per tal de millorar els models existents, es necessita conèixer millor com es comporten els fangs en termes de sedimentació.

D’aquesta manera, aquest projecte de final de grau té com a objectiu aplicar experiments ja realitzats amb mostres d’efluent primari a les mostres de fangs actius. A més a més, es pretén millorar els experiments ja realitzats amb mostres de fangs per intentar comprendre millor el comportament i les característiques sedimentaries d’aquests.

Paraules clau: Planta de tractament d’aigües residuals, Tractament secundari, Bioreactors, Tancs de sedimentació secundària, Fangs actius, Propietats de sedimentació.

RESUMEN

El agua es un recurso clave para la vida i requiere de la mejor calidad sanitaria posible para el consumo humano y el bienestar. El agua es también esencial para nuestros ecosistemas, ya que proporciona un hábitat natural para muchas especies de plantas y animales. Sin embargo, los recursos hídricos están bajo una presión creciente en muchas partes del mundo debido a la continua demanda creciente de agua limpia y la producción de grandes cantidades de aguas residuales. A este respecto, el objetivo principal de la planta de tratamiento de aguas residuales es eliminar al máximo los contaminantes del agua y obtener un efluente de calidad. Por esta razón, un buen funcionamiento y un buen rendimiento de una planta de tratamiento de aguas residuales es de crucial importancia para evitar una mayor contaminación y el agotamiento de los recursos hídricos.

Para la obtención de un efluente con la mínima cantidad de contaminantes, el tratamiento secundario llevado a cabo en los tanques de sedimentación secundaria, es un paso crucial. La separación de los fangos activos del agua se produce principalmente gracias a la sedimentación gravitacional de los copos que se forman espontáneamente. El problema se encuentra cuando los copos no presentan buenas propiedades de sedimentación, causando la presencia de fangos activos en el efluente. La eficiencia del proceso de sedimentación depende de factores físicos (diseño y operación de los tanques de sedimentación, la turbulencia provocada por la aireación, etc.) y factores químicos / biológicos (composición de las aguas residuales) y esto hace que el proceso sea muy complejo. Por esta razón, los bioreactores y los tanques de sedimentación secundaria se tratan como un sistema interactivo, ya que uno depende del otro.

El problema es que modificar los tanques de sedimentación no es siempre posible debido al espacio limitado disponible, así como de los fondos económicos y por tanto es necesario que los tanques existentes funcionen de manera eficiente. Además, la operación y el control también son factores limitadores importantes en plantas de aguas residuales convencionales. Debido a estos límites, es importante saber qué factores afectan al proceso de sedimentación de los fangos activos para poderlos controlar y crear lodos con buenas propiedades sedimentarias.

A pesar de la considerable investigación realizada en este campo, los factores que afectan a las propiedades de sedimentación de los fangos activos no se acaban de entender completamente. Con el fin de mejorar los modelos existentes, se necesita conocer mejor cómo se comportan los lodos en términos de sedimentación.

De esta manera, este proyecto de final de grado tiene como objetivo aplicar experimentos ya realizados con muestras de efluente primario a las muestras de fangos activos. Además, se pretende mejorar los experimentos ya realizados con muestras de lodos para intentar comprender mejor el comportamiento y las características sedimentarias de estos.

Palabras claves: Planta de tratamiento secundario, Bioreactores, Tanques de sedimentación secundaria, Fangos activos, Propiedades de sedimentación.

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ACRONYMS

AS	Activated Sludge
ESS	Effluent Suspended Solids
MLSS	Mixed Liquor Suspended Solids
RAS	Returned Activated Sludge
PT	Primary Treatment
PST	Primary Settling Tank
SBH	Sludge Blanket Height
SBT	Settling Batch Test
SST	Secondary Settling Tank
SVT	Settling Velocity Test
ST	Secondary Treatment
SVI	Sludge Volume Index
TSS	Total Suspended Solids
WWTP	Wastewater Treatment Plant

1. INTRODUCTION

1.1. WASTE WATER TREATMENT PLANT (WWTP)

In order to remove the pollutants from the municipal wastewater, it is used a Wastewater Treatment Plant (WWTP). The plant consists of three consecutive treatments steps: primary, secondary and tertiary treatment. (Soller, J. A., *et al*., 2003).

The primary treatment (PT) involves the removal of large particles using mechanical operations such as filtration, cut with blades, sedimentation, etc. During the secondary treatment (ST), organic compounds and nutrients are degraded from the wastewater by a variety of microorganisms. Later, the microorganisms are separated from the water. This ST is based on the Activated Sludge (AS) system. The AS system accelerates the natural purification process that occurs in water systems by overcoming the natural limitation for bioconversion such as limited aeration and limited amount of biomass (Henze, *et al*., 2008). Finally, in the tertiary treatment the objective is to remove residual constituents and to disinfect the effluent in order to destroy pathogens. The *Figure 1* shows the different treatment steps of a conventional WWTP.

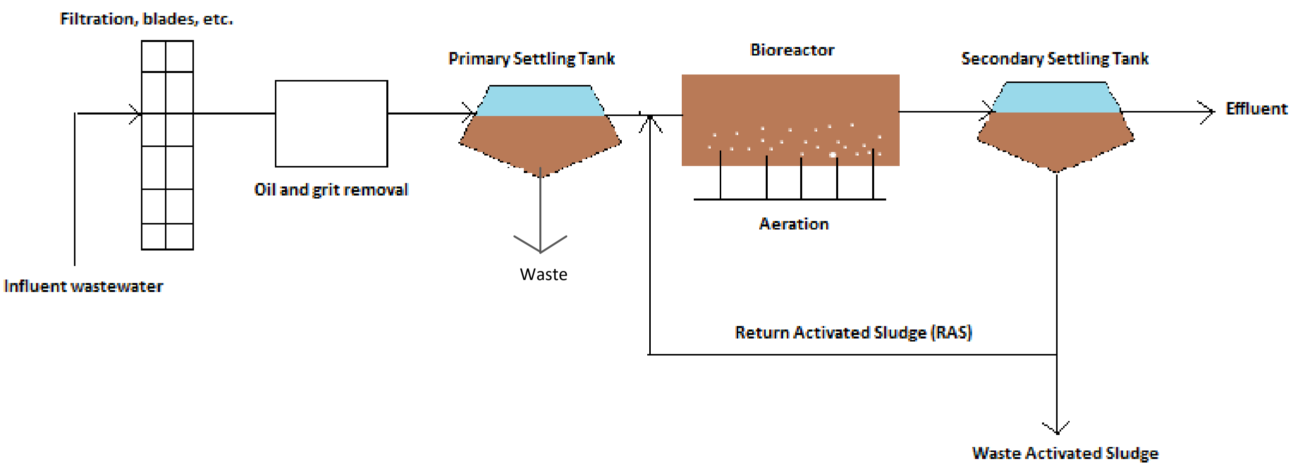

FIGURE 1. Diagram of a conventional WWTP.

1.1. SECONDARY TREATMENT (ST)

Despite of all the treatment steps, the experiments done in this report are based on the ST, more concrete in the Secondary Settling Tank (SST).

The ST takes place in the bioreactor and SST respectively. First of all, the wastewater is transferred from the Primary Settling Tank (PST) to the bioreactor. Inside the bioreactor, the wastewater is mixed with the AS, which is responsible for the conversion of organic compounds and nutrients into biomass. The biomass concentration in the tank is called the Mixed Liquor Suspended Solids (MLSS) concentration. There is an aeration system that supplies part of the microorganisms with oxygen for the aerobic bioconversion of the organic matter as well as creating zones for anoxic or anaerobic degradation of nutrients. The dissolved oxygen levels throughout the bioreactor are controlled by sensors. Once sufficient biological treatment is achieved, the mixed liquor is driven to the SST in order to be separated from the treated wastewater, which becomes secondary effluent. The main function of this tank is to separate the AS (dense phase) from the effluent (liquid phase) by gravitational settling. At the same time, part of the settled AS is recycled to the bioreactor in order to maintain the desired MLSS concentration. This AS is called return activated sludge (RAS). The remaining part is wasted. (Henze, M., *et al*., 2008).

1.1.1. SECONDARY SETTLING TANK (SST)

The SST has an important function in WWTPs, as it was said, that directly affects the effluent quality, being the final step in the ST, as well as the biomass inventory through the recycle of the separated microorganisms to the biological reactor.

The SST has to fulfill three important functions prior to discharge of the treated wastewater to the receiving waters: thickening, clarification and be a sludge storage tank.

-The **thickening** function means to produce a continuous underflow of thickened sludge for being returned to the bioreactor. The majority of the sludge mass that enters in the SST has to settle at high concentrations. If this function fails, the capability of the treatment plant will decrease due to the less recycled sludge to the bioreactor. Furthermore, well compacted solids decrease the costs related to sludge disposal and dewatering processes.

-The **clarification** function consists in the ability to capture as much as possible the AS particles that enter in the SST from the effluent by the action of gravitational settling. The AS is flocculent, so given it the right condition, flocs will be formed which are larger than individual microorganisms and are slightly denser than water, so they can settle. So is useful for reducing the concentration of small, discrete particles that don't have enough mass to settle in the SST. If this function fails, may result an increase of Effluent Suspended Solids (ESS) decreasing the purity of the effluent.

-Finally, the SST has to act as a **sludge storage tank**. Under high hydraulic loading conditions (e.g. periods of heavy rainfall) the SST needs to store sludge without causing an increase in ESS concentration. Under these conditions, sludge will be moved from the aeration tank to the SST. In order to prevent loss of sludge, the SST needs to be able to store this extra sludge. The storage function is mainly ensured by a proper design of the SST. (Torfs, E., 2016)

1.2. SETTLING

The settling process in the SST is a critical part of the ST process. Its performance is measured by the quality of the effluent and the quality of the thickened sludge. The thickened sludge must be thick enough to be able to be returned to the bioreactor to maintain the desired concentration of biomass; at the same time, the AS needs to have good settling properties for not to be present in the effluent.

The settling behavior of AS varies and may occur simultaneously among different regions in the SST. It can be classified in four settling regimes (*Figure 2*): **discrete non-flocculent settling** (Class I), **discrete flocculent settling** (Class II), zone settling or **hindered settling** (Class III) and **compressive settling** (Class IV).

When the particles are completely dispersed, there is no physical contact between them and the concentration is too dilute, the regime is called **discrete non-flocculent settling**. During settling, processes of collision and cohesion happen forming in that way larger flocs. These alterations in size and shape of the flocs change their settling velocity over time but they will still settle as individual flocs. This regime is called **discrete**

flocculent settling. The two discrete settling regimes are also known as clarification, because they occur in the clarification zone of a SST. Both settling regimes are of crucial importance to the performance of the SST as clarifier because it concerns particles that settle poorly, remain in the supernatant and are eventually carried over the effluent causing increased ESS concentrations.

In the **hindered settling** the particles settle collectively. In this regime, a distinct interface between the clear supernatant and the subsiding flocs is formed, called sludge blanket.

When the particles concentration increases, the flocs come into physical contact between them and they start to compact due to the weight. The settling behavior changes to **compressive settling**. (Torfs, E., *et al*., 2016)

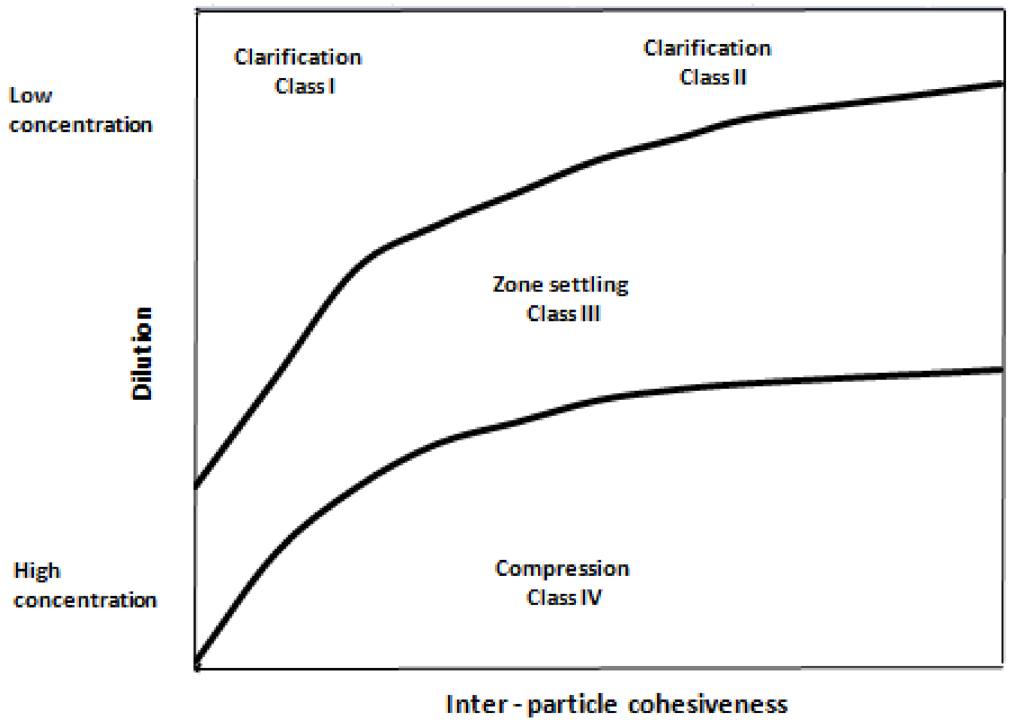

FIGURE 2. Settling regimes in a SST.

1.3. COMPOSITION OF ACTIVATED SLUDGE FLOCS

Activated sludge (AS) flocs are aggregates of suspended solids formed through physic chemical interactions between a mixture of different microorganisms such as bacteria, fungi, protozoa and metazoan, dead cells and particulate organic and inorganic material. (Wilén, B. M., 1995) A network of extracellular polymeric substances holds the different constituents together in one structure or floc. It has to be a good balance between the filamentous and floc-formers microorganisms. The first ones will provide a network which floc formers can attach to, resulting in large and strong flocs which are more resistant. Moreover, the filamentous network can also constitute a filter which removes small particles from the water producing a clear effluent. As such, both the excessive growth of filaments as well as floc formers may cause problematic sludge settling. For example, lower density flocs accompanied with a lot of filaments growing inside can result an open-structured floc that can cause poor AS sedimentation. Moreover, floc fragments may cause pin-point sludge, which are dispersed particles which have a slow sedimentation, are weak and small. (Torfs, E., 2016).

Floc size proves to be very useful to understand the influence of changes in process conditions such as substrate loading, sludge age or dissolved oxygen concentration. Due to the floc's biological nature, the complex and fragile structure and heterogeneous composition, affects the interpretation of the AS, leading to contradictory results. (Govoreanu, R., *et al.*, 2009)

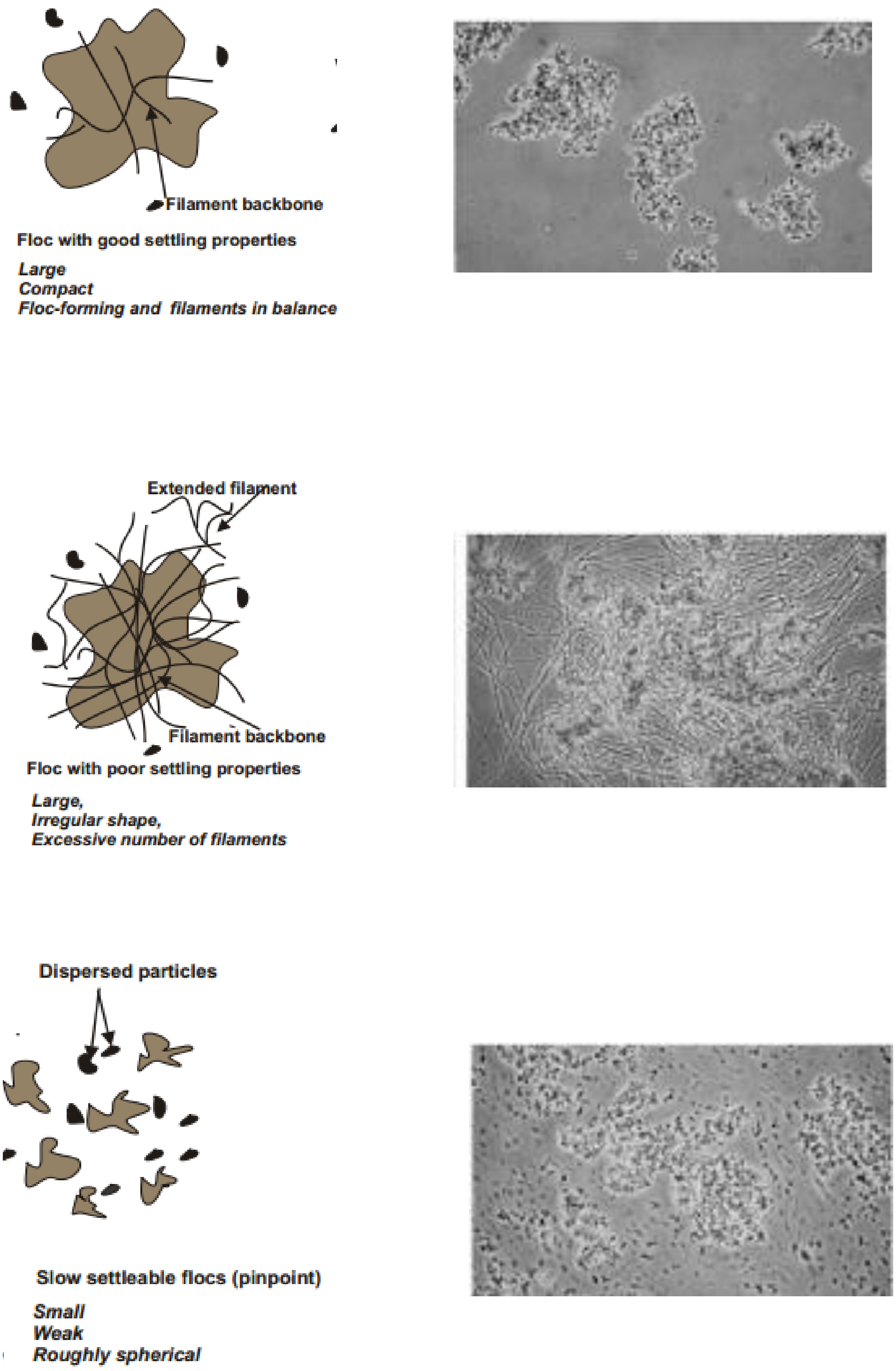

FIGURE 3. Representation of the three kinds of sludge flocs (Govoreanu, R., 2004) with the corresponding images from Jenkins, D., & Wanner, J., 2014.

2. OBJECTIVES

The quality of the effluent and the thickened sludge are directly related with the settleability parameters of the activated sludge (AS). For that reason, the AS needs to have good settling properties.
Therefore, is needed to better understand the settling behavior of the AS for improving the secondary treatment of the wastewater treatments plants obtaining in that way a high quality effluent and decrease the costs.

The above main objective is divided into the following sub objectives:

- How the use of different activated sludge concentrations affects to the settleability properties
- How the previous stirring up of the sample affects to the settleability properties

To assess the results of sub objectives, different sedimentation tests will be carried out and compared. The Sludge Volume Index (SVI), the Settling Batch Test (SBT) and the Setting Velocity Test (SVT).

3. METHODOLOGY AND MATERIAL

3.1. PILOT PLANT

The pilot plant is the waste water treatment plant (WWTP) where all the next experiments were done. It is a construction located inside the Université Laval in Quebec (Canada), which represents a conventional WWTP.

This pilot plant, as a conventional WWTP has two treatments, the primary and the secondary. The path that the wastewater that comes from the university residence (not artificial) follows is the next:

Primary treatment (PT):

-The wastewater passes through blades and a grid where the big particles (as toilet paper, hairs, plastics, etc.) are cut up and filtered. Once the big particles are broke, the water is stored in the **Storage tank** where there is a mixer that avoids the particles to settle. The water from this tank is the one that is used to feed the system with an incoming flow rate of 1.1 m^3/h.

- The wastewater, after the storage tank goes to the **Primary Settling Tank (PST)**. In this tank the big particles are separated by gravitational settling from the rest of the wastewater that continues its way till the two **bioreactors** with an incoming flow rate of 0.5 m^3/h. The operational conditions of the PST are:

-**Temperature:** 20-25 ºC
-**Conductivity:** 500-1000 uS/cm
-Total Suspended Solids (TSS): 50 – 200 mg/L
-Total Organic Carbon (TOC): 400 – 500 mg/L
-Chemical Oxygen Demand (COD): 120 – 150 mg/L
-pH: 6.5 -8.5
-K: 3-3.5 mg/L
-NH_4-N: ~30 mg/L

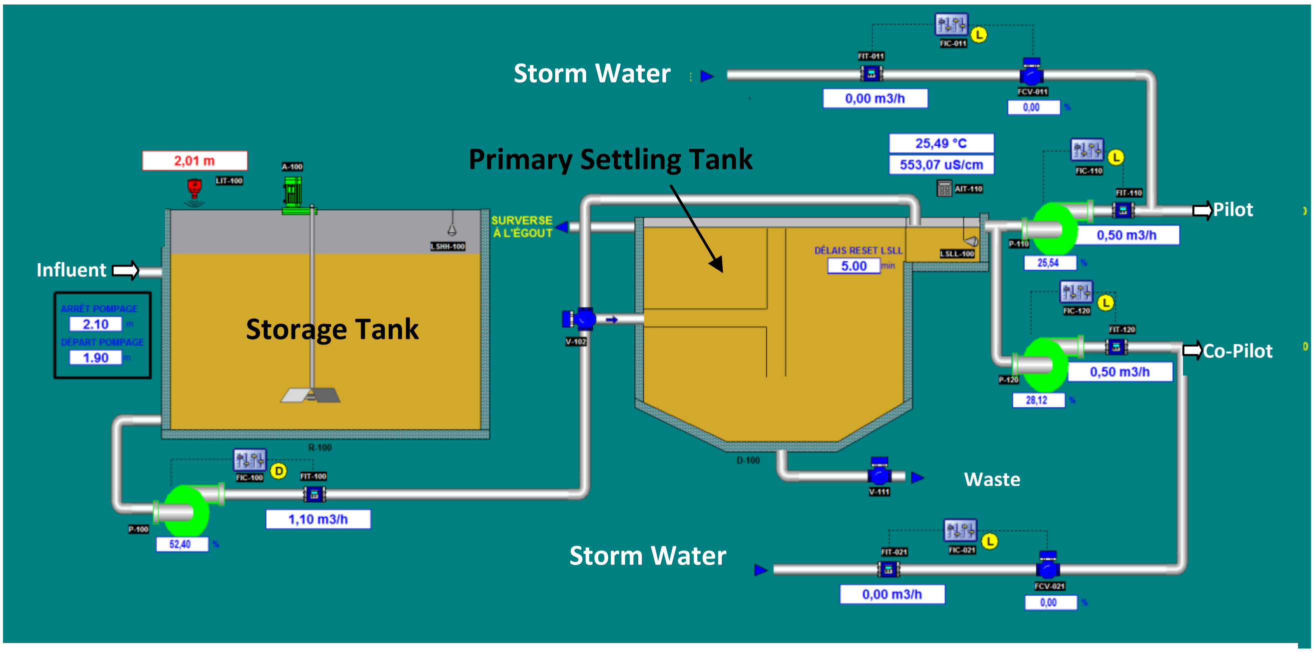

FIGURE 4. Representation of the PT of the Pilot plant. (Université Laval (Canada), 2016).

Secondary treatment (ST):

-One of the differences from the pilot plant and a conventional WWTP is that, instead of having one bioreactor, the pilot has two identical ones with a volume of 6.24 m^3 each one, called **Pilot** and **Co-pilot**. They have the same operational conditions but with the advantage that they can be changed. In that way, experiments can be done and the parameters such as temperature, aeration, sludge waste, etc. can be compared. The usual operational conditions of the bioreactors are:

- **Total suspended solids (TSS):** 2000-5000 mg/L
-**Temperature:** 17-20 ºC
-**Dissolved oxygen:** 0.1 – 4 mg/L

The Pilot and Co-pilot are divided in five bioreactors where the two first ones don't have aeration, are anoxic; and the three last ones are aerated so they are aerobic.

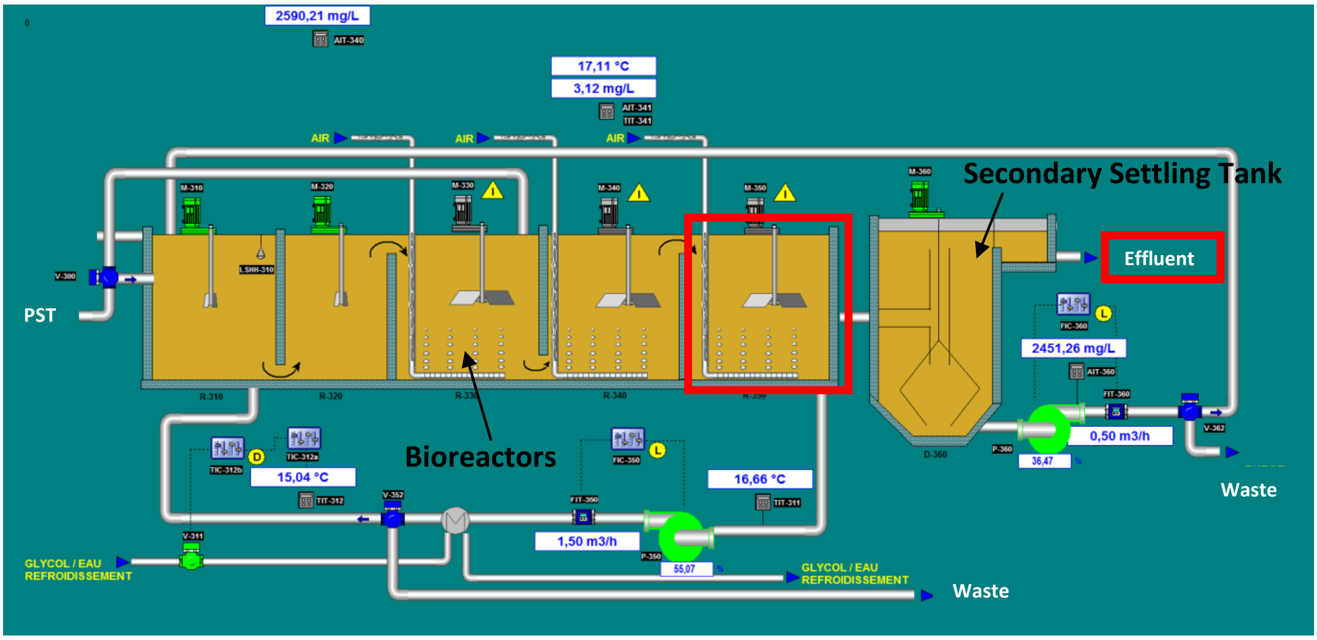

FIGURE 5. Representation of the ST of the Pilot plant. (Université Laval (Canada), 2016).

-The second part of the ST is the **Secondary Settling Tank (SST).** The activated sludge (AS) that comes from the bioreactor goes to the SST where the AS is separated from the effluent by gravitational settling. At the same time, some part of the AS is returned to the bioreactors (RAS). Moreover, some part of the AS is wasted for maintaining the internal conditions stable due to the AS is growing through the time. The usual operational conditions for the SST are:

-**Solids retention time:** 12-13 days.
-**Sludge waste flow rate**: 0.50 m^3/h
-**Returned Activated sludge (RAS) flow rate:** 1.5 m^3/h
-**Total suspended solids of the RAS:** 2500 – 3000 mg/L

-The samples for carrying out the tests were recollected in the 5th bioreactor of the Pilot and the effluent highlighted in red in the *Figure 5.*

3.2. THE SLUDGE VOLUME INDEX (SVI)

The Sludge Volume Index (SVI) is based on the volume that sludge occupies after a fixed period of settling. This method is defined as the volume (in ml) occupied by 1 g of sludge after 30 min settling in a 1L cylinder column. There are some issues with the SVI test as a measure of sludge settleability. The most important one is its dependency on the sludge concentration. Particularly at higher concentrations, measured SVI values can deviate significantly between sludge concentrations. (Torfs, E., *et al.,* 2016). Moreover, SVI measurements have been found to be influenced by AS composition and its characteristics.

3.2.1 METHODOLOGY

The sample to be analyzed, which volume is 2L, has to be well mixed and pulled in a 2L graduated cylinder column. Once the column is full, the timer is started and the sludge sample is allowed to settle. After 30 min of settling, the height of the sludge blanket has to be read. When the reading step is done, the sample is well mixed again and three subsamples are analyzed for TSS. As soon as the volume of the sludge is known after 30 min of settling and also, the concentration of the sample, it has to be applied the next *Equation 1* for knowing the final result.

$$SVI = \frac{\mathrm{SV}_{30}}{X_{Tss}} \qquad \text{Equation 1}$$

Where:

X_{Tss} (g/L): Concentration of the sample

SV_{30} (ml/L): Volume occupied by the sludge after 30 min of settling

3.3. SETTLING BATCH TEST (SBT)

This test is useful for obtaining more detailed information of the sludge settling behavior, which makes possible to investigate the settling behavior of sludge at different settling times.

The settling behavior is made up of different phases of settling. Looking the *Figure 6,* it can be seen an approximation of the points where the different phases start and end.

At the beginning of the test, due to the disturbances caused by the filling of the column, the sample needs to recover. This first phase that goes from the beginning of the test till Point (a) is called **lag phase.** Once the sample is recovered from the turbulences the **zone settling phase** starts. This second phase starts at Point (a) till the Point (b) and is easy to differentiate due to the declination of the SBT curve. When the sludge blanket reaches the transition layer, which is a layer of constant thickness and is formed by particles coming from the decreasing hindered settling layer and particles coming from the increasing compression layer, starts the **transition phase** at the Point (b). The **transition phase** finishes when the **compression phase** starts Point (c). The compression phase is difficult to identify due to it’s not easy to see at the exact point where the sample stops settling. (Torfs, E., *et al.,* 2016).

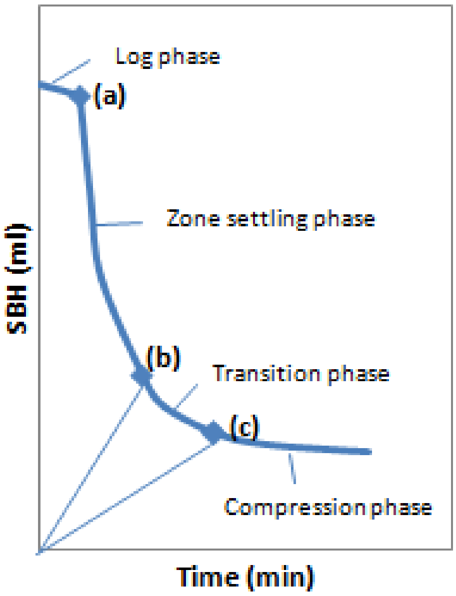

FIGURE 6. Evolution of the sludge blanket height (SBH) over the time. The four settling phases are indicated.

3.3.1 METHODOLOGY

The sample to be analyzed, which occupies a volume of 2L, has to be well mixed and poured in a 2L graduated cylinder column. At the same time, the timer has to be started to keep track of the duration of the experiment while the sample is settling. During the test, the position of the suspension-liquid interface is measured at different time intervals. The times for measuring the SBH are 0, 0.5, 1, 2, 3, 4, 5, 10, 15, 20, 30 and 45 min. At the beginning of the test, the SBH is typically measured more frequently, as the sludge is settling relatively fast. Later in the test, the frequency of the measurements is decreased, because the interface is moving more slowly. (Torfs, E., *et al.,* 2016). After 45 min of settling, the sample is well mixed again and three subsamples are analyzed for TSS.

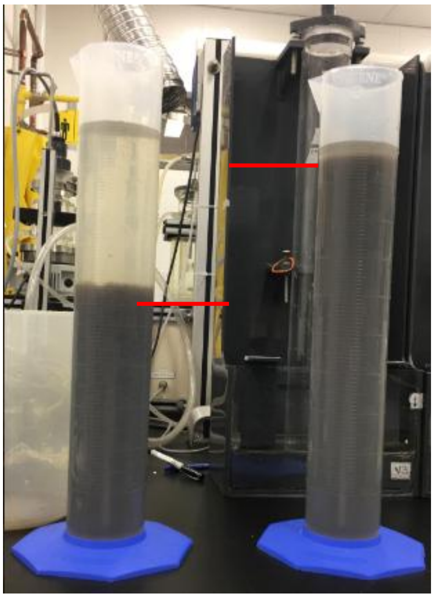

FIGURE 7. Image of two SBT columns at different settling times, indicating the suspension-liquid interface or SBH.

3.4. SETTLING VELOCITY TEST (SVT)

The Settling Velocity Test (SVT) measures the settling velocity of particles in a column under static conditions. The test provides insight into the behavior of particles present in a wastewater sample in order to obtain an idea about its composition. Also, the method directly measures the distribution of settling velocities in representative wastewater samples. The knowledge of the settling velocity distribution can be used to determine an optimal HRT and corresponding load reduction to the treatment plant. (Torfs, E., *et al.,* 2016)

3.4.1 METHODOLOGY

The sample to be analyzed, which occupies a volume of 5 L, is homogenized. Before starting the experiment, it has to be kept 0.5 L for measuring the initial concentration doing a TSS test. The TSS has to be done for triplicate and use a volume approximately of 100 ml for each replica. The remaining volume (4,5L), once again it's homogenized and poured into the trough, where it is sucked up at the same time by means of vacuum pressure into the settling column. When the water level in the column has reached approximately 60 cm, the valve from the pump is closed, and the column is held in a vacuum pressure state for the remainder of the measurement. At that time, the timer starts. An aluminum plate filled with distilled water is immersed in the trough and glided along the guiding tray underneath the column base at time 0 min. The times for sampling are 2, 4, 6, 12, 16, 32, 64 and 128 min. Once sedimentation time has elapsed the times implemented at the beginning, the plate has to be glided and replaced by the new one carefully. The sampling step is the crucial step, the movements have to be done prudently for not to disturb the balance inside the column. Also, for don't lose the sample at the time of taking out the plate from the trough. The particles that have settled in the plates have to be filtrated and later measure its mass.
When the test finishes, the last step is to recollect the volume left inside the column, for being able to measure its final concentration. Is needed to do the TSS for triplicate and use a volume approximately of 200 ml for each replica (Chebbo, G., & Gromaire, M. C., 2009).

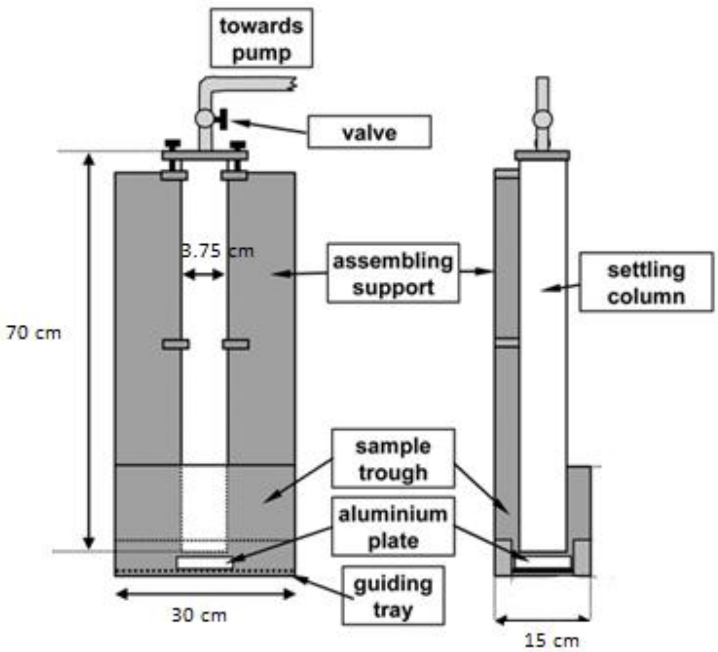

FIGURE 8. Diagram of a SVT equipment.

After the operational steps, a mass balance calculation is performed to estimate losses or gains of solids during the experiments and thus to assess the quality of the measurement. The percentage mass balance error (E %) is calculated using the *Equations 2*, *3*, *4* and *5.* The E% value has to be between ±15% for the test to be succeed.

Initial mass, M_{ini} (mg): $$M_{ini} = \frac{C_{ini} H \pi R^2}{1000}$$ *Equation 2*

Final mass, M_{fin} (mg): $$M_{fin} = \frac{C_{fin} H \pi R^2}{1000}$$ *Equation 3*

Collected settled mass, M_{set} (mg): $$M_{set} = \sum_i m_i$$ *Equation 4*

Percentage of error on the mass balance, E % (%): $$E\% = \frac{M_{ini} - (M_{set} + M_{fin})}{M_{ini}}$$ *Equation 5*

Where:

- **C_{ini} (mg/l):** initial concentration
- **C_{fin} (mg/l):** final concentration
- **m_i (mg):** mass of particles recollected in the aluminum plate between time t_{i-1} and t_i
- **H (cm):** water height inside the column
- **R^2 (cm):** column radius

For performing the reproducibility tests in order to confirm the results for a SVT, two measurement data processing methods were developed by Chebbo, G., & Gromaire, M. C. (2009) and may be easily implemented by means of a series of macros written in Excel. In the obtained graphic, the settling distribution curve has not to be completely vertical or horizontal, because it means that all the particles have the same velocity and they settle at the same time too. An example of a typical settling distribution curve for a wastewater sample is showed in the *Figure 10.*

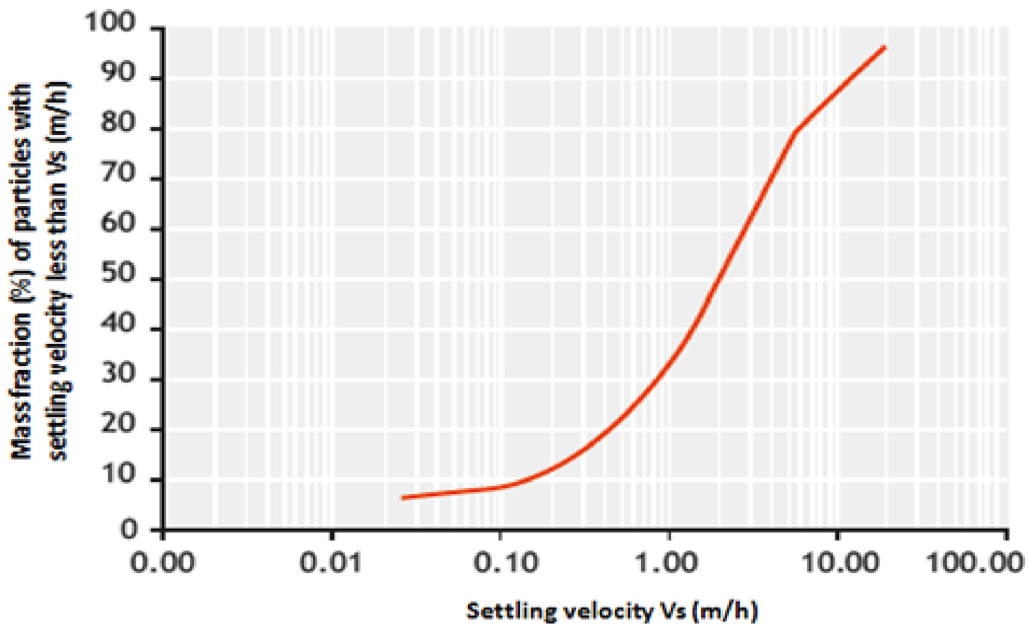

FIGURE 10. Representation of a typical settling velocity distribution curve f (Vs) for a wastewater sample.

From the pilot plant, several samples were obtained in order to better understand the settling behavior of the AS. Thus, samples from the 5th bioreactor from the Pilot were collected for different periods of time, but not in a regular way. The samples were analyzed to identify the effect of the concentration and stirring conditions to the settleability parameters. The settling parameters analyzed were the settleability, settling behavior and settling velocity. Thus, the next experiments (**SVI**, **SBT** and **SVT**) were carried out.
Before doing the tests, some hypotheses were thought in order to guide the tests and allow concrete conclusions to be written from the project.

-The particles of the samples that were stirred up will have worse settleability than the ones that were not stirred no matter the concentration of the sample.
-The samples that were stirred up won't present defined settling phases in the SBT curves no matter the concentration of the sample.
-The particles of the samples that were stirred up will settle slowly than the ones that were not stirred no matter the concentration of the sample.

4.1. SLUDGE VOLUME INDEX (SVI)

The Sludge Volume Index (SVI) was carried out to see if there is a relation between the SVI value and the AS concentration, due to the concentration is an issue as a measure of sludge settleability. Particularly, at higher concentrations, SVI values can deviate significantly between sludge concentrations. According to Torfs, E., *et al. (*2016), typical SVI values for AS can be found between 50-400 ml/g, where 50 ml/g indicates a sample with very good settleability and 400 ml/g a sample with poor settling properties.

The *Figure 11* represents the SVI values (ml/g) obtained for each concentration (g/L) for different AS samples collected throughout 3 months (d/m/yy). Observing the results obtained, there is no a relation between the concentration and SVI values.
It may say that SVI measurements are not only influenced by the concentration of the sample, there must be a number of factors such as the composition of the AS, floc size, surface properties, etc as Torfs, E. *et al.* (2016) said.

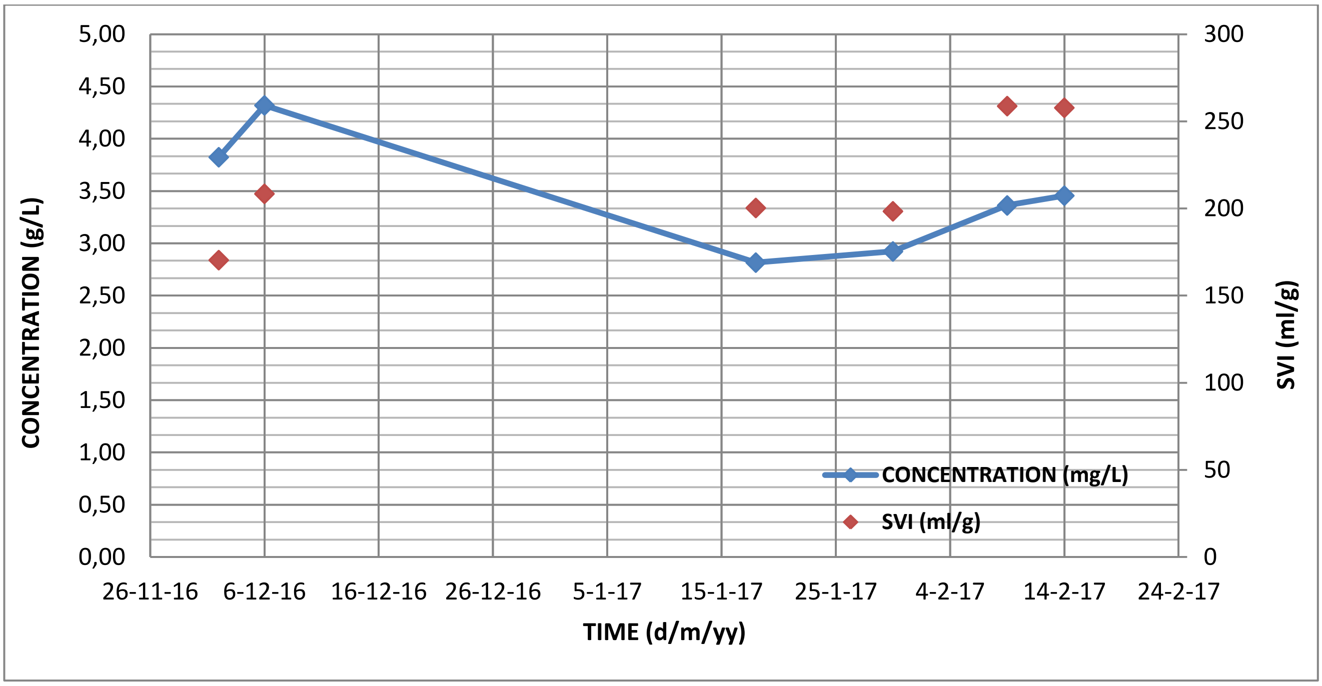

Figure 11. Representation of the SVI values (ml/g) for each concentration (g/L) for AS samples collected throughout 3 months.

As it can't be compared the different samples collected in different period of time due to the variability in the composition, the other parameter that was wanted to check was to see if the stirring up of the sample may affect to the settleability parameters, due to stirring the sample reduces wall effects, bridge formation effects thereby creating conditions more closely related to those prevailing in the sludge blanket in SST. (White, M.J.D., 1975).

In order to see the differences, the samples of AS from the 5th bioreactor of the pilot were diluted. This step differs from the standard SVI by performing an additional dilution step prior to settling. The sludge is diluted with effluent from the Pilot trying to have a concentration range (high, medium and low) near the optimal concentration for the SBT (*see point 4.2)* that was 2.5 g/L. After the dilution, it was stirred up during 20 min at ~200 rpm with a stirrer (*PHIPPS & BIRD STIRRER, model 7790-400 (120V 50-60 Hz)*).

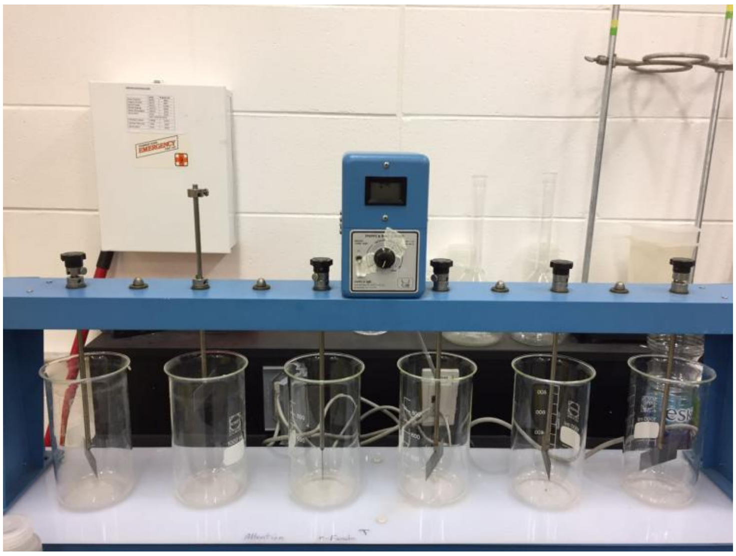

Figure 12. Image of the stirrer *PHIPPS & BIRD STIRRER, model 7790-400 (120V 50-60 Hz).*

DATE	NORMAL OR STIRRED	CONCENTRATION (g/L)	SVI (ml/g)
03/02/2017	NORMAL	3,58 (high)	193,50
03/02/2017	STIRRED	3,54 (high)	237,79
10/02/2017	NORMAL	3,22 (medium)	258,23
10/02/2017	STIRRED	3,21 (medium)	236,90
15/02/2017	NORMAL	2,37 (low)	194,71
15/02/2017	STIRRED	2,26 (low)	269,62

Table 1. Obtained SVI values (ml/g) for each concentration (g/L) for different samples (normal or stirred).

The SVI values obtained for the different samples are shown in the *Table 1.* It is compared which sample has better settleabilty, the one which was stirred or, for the contrary, the one that wasn't for different concentrations. As a result, for the high and low concentrated samples, the ones that were not stirred present better SVI values. On the other hand, for the medium concentrated samples, the ones that were stirred present better settleabilty. Furthermore, comparing the normal samples in order to see the effect of the concentration on the settleability, the ones that present better SVI values are the low and high concentrated samples.

4.2. SETTLING BATCH TEST (SBT)

The Settling Batch Test (SBT) was carried out to see how the concentration affects to the settling behavior and which the optimal one is to see the different settling phases for the AS present in the pilot plant. Thus, different concentrations of samples were tested at the beginning.

The *Figure 13* represents the different SBT curves obtained for the experiments done according to the *point 3.3.1 Methodology* using different concentrations. Each curve represents the evolution of the SBH (L) over time (min) during the test.

For being able to determine which concentration is the optimal for see the settling phases, the *Figure 13* is compared with the *Figure 6.* Doing the comparison of both of us, experimental and theoretical, a relation between the phases of the curve, is observed. The *Figure 13* shows that the most concentrated the sample is, the most difficult is to observe the settling phases. The settling zone phase can be overwhelmed by compression very early in the test, being difficult to see clearly the phases between. In addition, at highest concentrations, the interface, also called sludge blanket is well defined and easy to identify. In the other hand, with lower concentrations, the sample arrives to the compression phase in a few minutes from the start of the test, being complicated to see the different phases as well. Also, with dilute concentrations, it may be difficult to determine the location of the sludge blanket height (SBH).

Furthermore, none of those samples tested draws the expected SBT curve. It was wanted to the sludge blanket to settle below 0.4 L after 30 min, but only two of the samples tested behave in that way. One of them, having a concentration of 0.68 g/L, was so difficult to read the SBH during the experiment, thus, is not the optimal concentration for carrying out the test even though it seems to have good settleability. Nonetheless, it can be seen that the best concentrations of the samples for carrying out the test are around 2.5 g/L. The reasons are the facility for the worker at the time of reading the SBH and also, the different phases can be approximately seen using this concentration. Furthermore, in preceding SBT experiments (Torfs, E., *et al.,* 2016) was used a concentration of 2.93 g/L for carrying out the test, which is an approximate number.

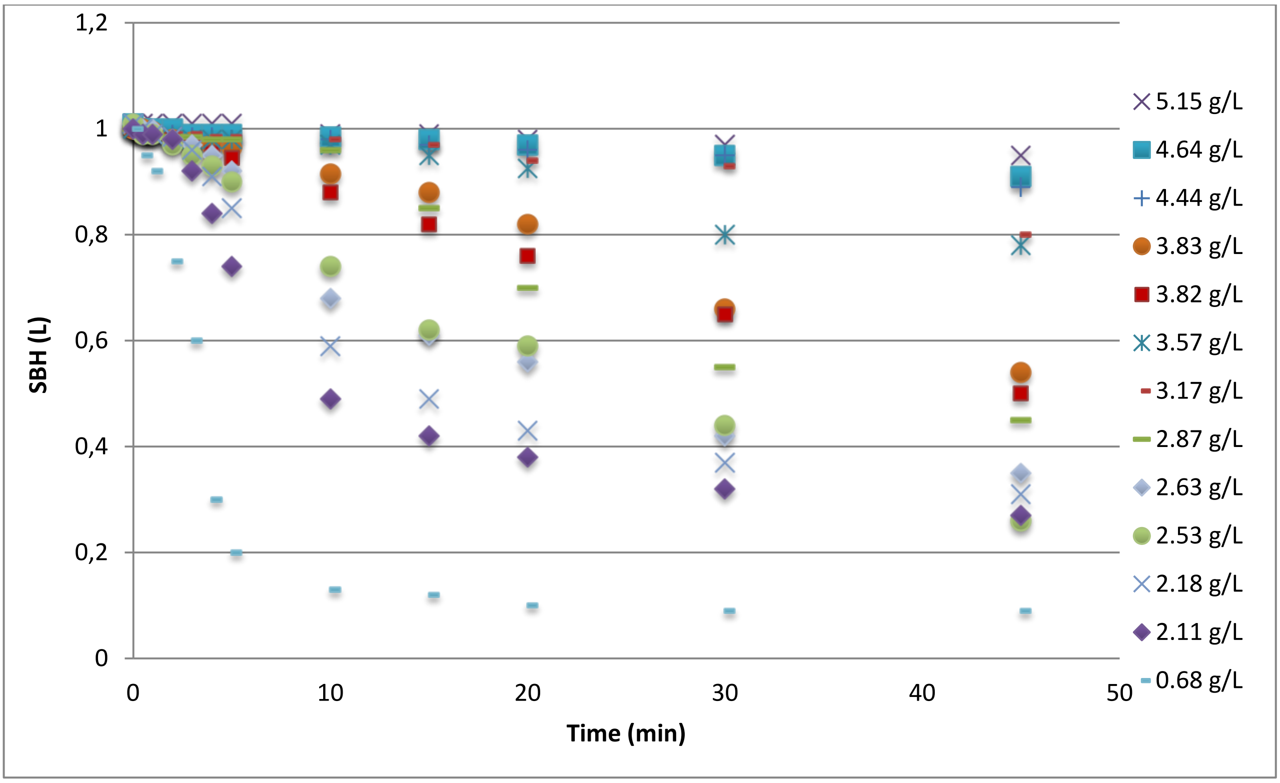

Figure 13. Representation of the SBH (L) at different time (min) for different concentrations (g/L).

Another parameter that was checked was the sampling time. The sampling time used in the test was the standard: 0, 0.5, 1, 2, 3, 4, 5, 10, 15, 20, 30 and 45 min. In the *Figure 13* it can be seen that the transient of the AS was long, so there is a period of time at the beginning of the test where the sample behaves in the same way no matter the concentration. So, for that reason, for being able to appreciate the little changes between concentrations at the beginning after the transit, the procedure was improved changing the time of reading the SBH.

It was incremented after the first 5 min. Instead of reading the sample at 0.5, 1, 2, 3, 4, 5 min and directly to 10 min; the sample should be read every minute after the first 5 min till arrive to 10min; it means to read at 0.5, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30 and 45 min. In that way, more accurate information will be recollected and the curve will be more precisely drawn.

Once the methodology of the SBT was improved, the next step was to know how the stirring up of the sample affects to the settling behavior.

In order to see the differences between stirred up or not and at the same time between different concentrations, the samples of AS from the 5th bioreactor of the pilot were diluted trying to have a concentration range (high, medium and low) near the optimal 2.5 g/L set before. After the dilution, the samples were stirred up during 20 min at ~200 rpm with a stirrer (*PHIPPS & BIRD STIRRER, model 7790-400 (120V 50-60 Hz)*). Once the time was elapsed, the SBTs were started as fast as possible without letting the sample settle or the flocs to compact.

The *Figure 14* shows the different SBT curves obtained after the stirred up and without the stirring of the samples for different concentrations. Each curve represents the evolution of the SBH (ml) over time (min) during the test for all the samples.

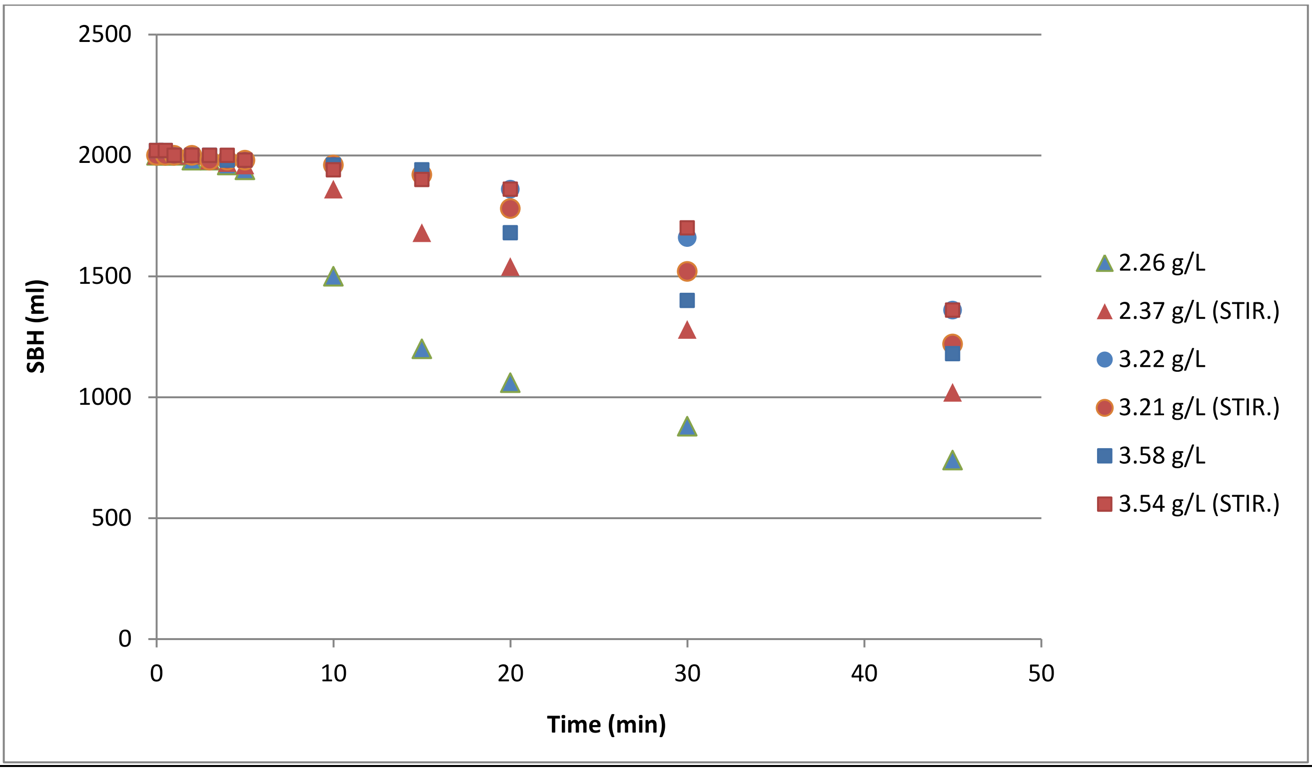

FIGURE 14. Representation of the SBH (ml) at different time (min) for different concentration samples after stirring up (red points) or not (blue points).

When the samples are stirred up, they settle slower than the samples without stirring. For example, after 30 min, the SBH values are higher for the stirred samples. The exception appears with the medium concentrated samples (3.22 and 3.21 (STIR.) g/L) that behave in the opposite way when are stirred.
The stirred samples, as they have a slower settling, makes more difficult seeing the different settling phases in comparison with the same sample without stirring for the same period of time. Furthermore, comparing the normal samples in order to see the effect of the concentration on the settling behavior, the one that draw better the settling phases is the low concentrate one, that have a similar concentration value (2.26 g/L) to the optimal one that was set before (2.5 g/L).

4.3. SETTLING VELOCITY TEST (SVT)

The Settling Velocity Test (SVT) test was carried out in order to check the settling velocities of the AS. The SVT is an experiment that was only carried out with samples from the primary treatment (PT) of the pilot plant, where the settling velocity depends on the individual properties of particles. Due to its utility, was wanted to be seen if it was possible to execute it with samples from the ST of the pilot plant. As the characteristics of both samples are different from each other and they may behave in a different way, it was wanted to redefine the parameters and protocol of the SVT for using it with ST samples. With AS samples it is challenging to measure the settling velocities due to the variety of densities, shapes and sizes of suspended particles.

After different SVT done with AS samples, the protocol started to be changed. First of all, the time of sampling was modified. This change was made for avoiding the clogging of the filters when the total suspended solids (TSS) test is carried out for knowing the mass of the particles recollected.

The modification of the time was done at the beginning of the test that is when the particles settle faster. The standard sampling time was 2, 4, 8, 16, 32, 64 and 128 min; and was modified to 2, 4, 6, 8, 12, 16, 32, 64 and 128 min. In that way, the frequency of the sampling was incremented but there was an inconvenient; the operator has to be fast, precise and careful at the moment of changing the aluminum plates when sampling, for not to disturb the equilibrium inside the column and for not to lose particles at the time of taking out the plate.

The second parameter changed was the sample concentration used. Concentrations of particulate matter in AS are relatively high compared to concentrations in PST. For that reason, before carrying out the test, the sample has to be diluted with the effluent water. Therefore, different test were performed with samples from the 5th bioreactor of the pilot for guessing, approximately, which is the optimal concentration to make easy the operator's work and for obtaining good results.

The settling velocity distribution curves obtained testing different concentrations are presented in the *Figure 15.* It has to be read from right to left due to the particles that settle at the beginning of the test have high velocity than the ones which settle at the end. Observing the curves, none of them are completely vertical or horizontal, so it helps to say that the optimal concentration has to be around these numbers.

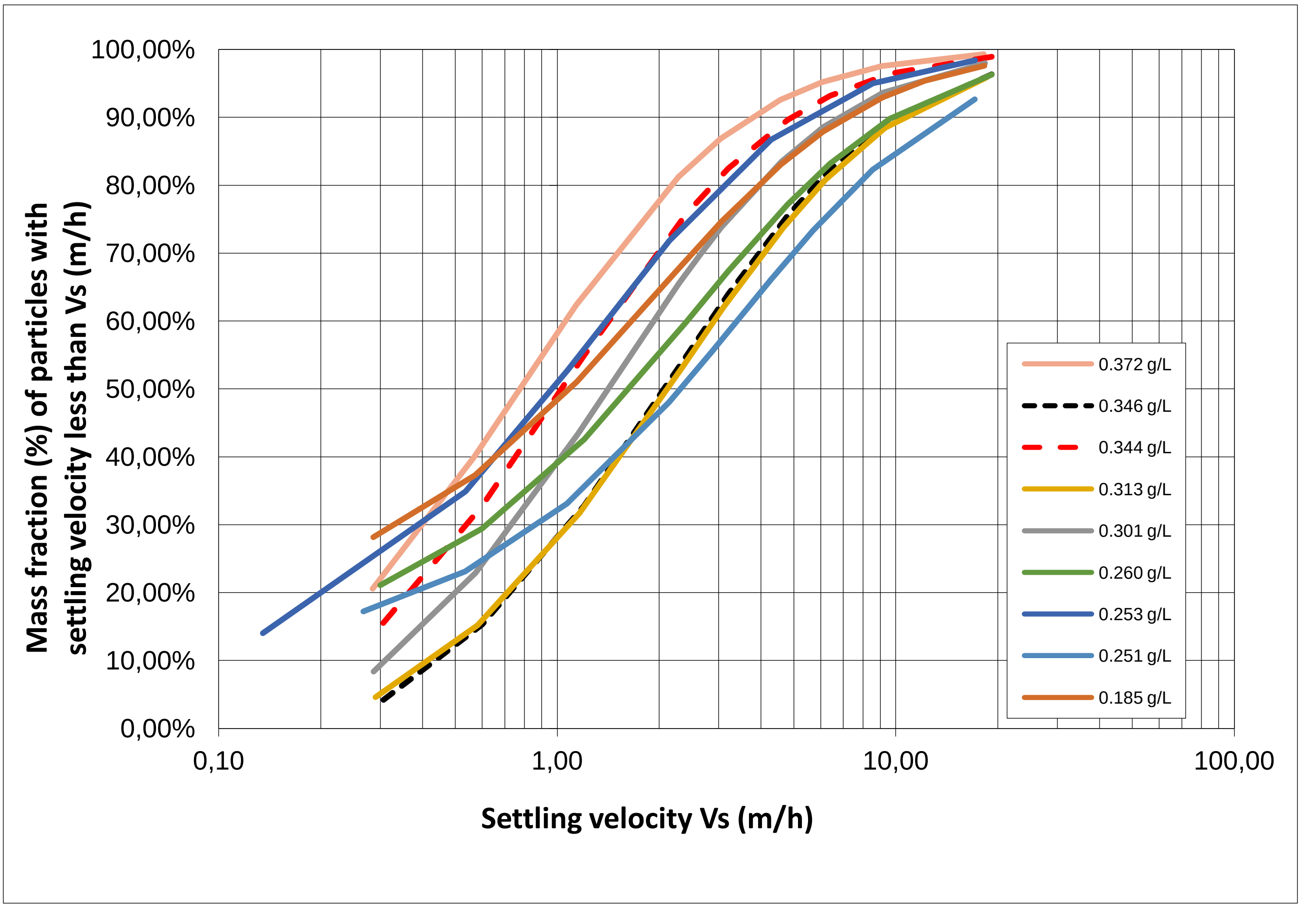

FIGURE 15. Representation of settling velocity distribution curves f (Vs) for different concentrated samples.

As it was said before, the SVT will be successful when the percentage values of error on the mass balance are within ±15%. Thus, the curves of the samples with an error value inside the range were accepted as succeed and the concentration average of those samples have been calculated for setting the best concentration for carrying out the test. The optimal one was 0.276±0.03 g/L, having an error of ±8.6% (*Table 2*).

This set concentration value is a reference value and it can change depending on the height and radius of the column used, the different AS particles from size and density, the operator's work, etc.

INITIAL CONCENTRATION (g/L)	0,251	0,253	0,260	0,301	0,313	0,186	0,344	0,346	0,372
E% ON THE MASS BALANCE	-12%	-3%	-13%	15%	10%	-20%	21%	16%	19%
CONCENTRATION AVERAGE (g/L)	0,276					0,312			

TABLE 2. Percentage of error on the mass balance values for each SVT at different concentrations (g/L). Also appears the concentration average (mg/L).

Once the protocol was improved for AS samples, the next step was to know how the stirring up of the sample can affect to the settling velocity.

In order to see differences, the samples of AS from the 5th bioreactor of the pilot were stirred up during 20 min at ~200 rpm with a stirrer (*PHIPPS & BIRD STIRRER, model 7790-400 (120V 50-60 Hz)*). When the time was elapsed, the samples were diluted trying to have a concentration range (high, medium and low) near the optimal 0.276±0.03 g/L, and the experiment started. At the same time, the same sample without stirring was diluted and parallel SVT started too.

The *Figure 16* represents the different settling velocity distribution curves after the stirred up and without stirring of the samples for different concentrations.

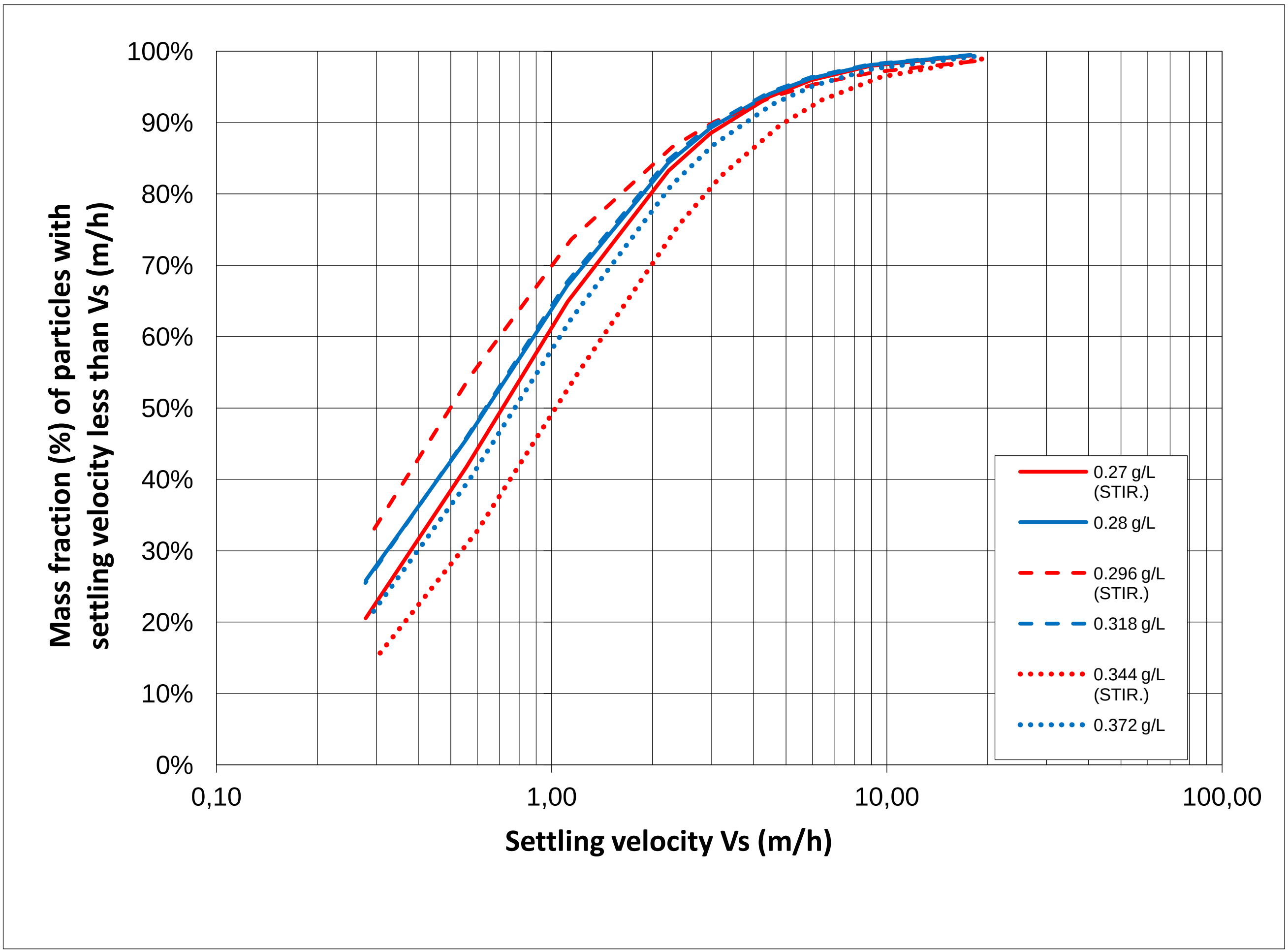

FIGURE 16. Representation of settling velocity distribution curves f (Vs) for different concentrated samples after stirring up (red) or not (blue).

When the samples are stirred up, there are a higher percentage of particles that have faster velocities than the samples without stirring. The exception appears with the medium concentrated samples (0.296 and 0.318(STIR.) g/L) that behave in the opposite way. Furthermore, comparing the normal samplesin rder to see the effect of the concentration on the settling velocity, the one that is more concentrated (0.372 g/L) present a higher percentage of particles that have faster velocities than the other concentrations tested (medium and low).

4.4. DISCUSSION

As was said above, the aim of the project was trying to better understand the settling behavior of the AS. For that reason, different concentrations of the samples were tested and moreover, it was tried to change the structure of the flocs by stirring the AS samples. The results obtained for the different samples and settling tests (SVI, SBT and SVT) are described in the *Table 3*.

		SETTLEABILITY PARAMETERS FOR EACH TEST		
STIRRED OR NOT SAMPLE	**CONCENTRATION**	**SVI**	**SBT**	**SVT**
NORMAL	HIGH	Better settleability	The settling phases are easy to see.	Particles have lower settling velocity
STIRRED		Worse settleability	The settling phases are less easy to see.	Particles have higher settling velocity
NORMAL	MEDIUM	Worse settleability	The settling phases are less easy to see.	Particles have higher settling velocity
STIRRED		Better settleability	The settling phases are easy to see.	Particles have lower settling velocity
NORMAL	LOW	Better settleability	The settling phases are easy to see.	Particles have lower settling velocity
STIRRED		Worse settleability	The settling phases are less easy to see.	Particles have higher settling velocity

TABLE 3. Settleability parameters for each test (SVI, SBT and SVT), sample (stirred up or not) and concentration (high, medium and low).

Assessing the obtained results for the SVI and SBT tests, it was seen that the samples that were stirred didn't present defined settling phases for the SBT curves using the high and low concentrated samples. The big flocs were broke, so the particles were more dispersed having a discrete non-flocculent and flocculent settling. It made confuse the reading of the sludge blanket height (SBH). Furthermore, the big flocs couldn't trap the small particles making worse the settleability obtaining in that way, high SVI values. For the contrary, the medium concentrated samples when were stirred, presented the opposite results. It was easy to read the SBH values defining better the different settling phases for the SBT curves, as well as the SVI values were lower. Those results were close to the first hypotheses that were set out. In addition, the stirring up causes the breaking of the big flocs creating in that way, little and less dense flocs. For that reason it was thought that the particles would settle with a slowly settling velocity when they were stirred. But doing the SVT tests, for the low and high concentrated samples that were stirred, the particles settle faster than the ones that weren't. Although, the contrary happened for the medium concentrated samples that its particles, when were stirred, settled slower than the particles from the samples that weren't. The reason why the medium concentrated sample behaves in a different way is unknown yet. Although the stirring changes the settling process, the direction and magnitude of change depends on the sample.

At the time of comparing the normal samples in order to see the effects of the concentration in the settleability of the AS, the results obtained seem to be contradictory. It was thought that when the samples are more concentrated, the particles have higher velocities and the SVI values should be lower meaning that the sample has good settling properties. But the results obtained, seem to be contradictory. For example, for the high concentrated samples, they presented higher SVI values and to see the settling phases was more difficult due to the sample arrives to the compressive phase earlier, but surprisingly, the particles had faster settling velocities than the other concentrations used.

There is an important point that has to be explained, because may be one of the reasons why those medium concentrated stirred samples diverged from the others.

Before the realization of some of the tests described, the pilot plant suffered different issues. The most important and critical one, was that the pump which supplies the wastewater to the Pilot and Co-pilot from the PST (Pump 100), suddenly broke, comporting in that way the totally stop of the pilot plant. The reparation of the Pump 100 took long time for diverse reasons. Due to this important problem, the microorganisms composing the AS, started to die. The faster solution was to start to feed the bioreactors with the wastewater from the storage tank using two auto samplers (*HACH, SIGMA AWRS SAMPLER, model 3540SDR (115V-60Hz)*). The time of feeding per day was 4-5 hours approximately from Monday to Friday during the middle of December 2016, January 2017 and February 2017.

This situation was a critical situation for the entirely pilot plant, but even more for the habitat of the bioreactors. There were problems with foaming; the metazoan microorganisms started to die and extremely situations appeared. This unusually conditions changed the characteristics of the AS; it means that its particles behaved different in terms of settling.

This out of the ordinary situation wasn’t that bad, it was useful to see how the AS behaves in an extremely environment. Although, more experiments should be done with normal conditions of the pilot plant for being able to compare and see if this unusual situation affected to the tests and check if the results are reliable or not.

5. ETHICS AND SUSTAINABILITY

The increase of the world population in recent decades has led to strong demands of well-being for its people, combined with overwhelming pressures on natural resources. One of the main resources affected is the hydraulic resource, in other words the water.

The treatment of wastewater is a vital aspect to consider, as well as the pollution and degradation that may generate and moreover for the possible reutilization of this resource. One of the main problems is that the treatment of the wastewater has a high cost involved. For this reason, water purification and sanitation systems have to improve their operation and structure in order to reduce costs and in that way reach the supply of all populations.

In order to collaborate with this research and improvements, this project has been based on trying to better understand the sedimentation behavior of the activated sludge (AS) in secondary settling tanks (SST) in order to improve the secondary treatment (ST) of the wastewater treatments plants (WWTP) with the objective to obtain a better quality effluent at the lower cost.

6. CONCLUSIONS

The performance of a secondary settling tank (SST) is characterized by different regimes of settling that occur simultaneously at different locations in the SST. These different settling behaviors contribute to a proper control of the biomass inventory by recycling a thickened activated sludge (AS) to the bioreactor and also, are responsible for a proper clarification of the AS from the water to ensure a good effluent quality. The work presented above provided new insights into the settling properties of the AS in a SST through the performed tests and analysis.

The stirring up of the samples seem to not be an advantage in order to improve the settleability of the AS samples. When the samples are stirred they present worse settleability no matter the concentration, except for the medium concentrated samples, that as said it is not known why behave in a different way.

The concentration of the samples seems to have an important paper in the settling behavior of the AS. Even though the results may be contradictory, it can’t be compared the results from SBT tests with the SVT tests, because the concentration of the AS samples used for each one were different and as said, it may be the reason of the contradictions.

During the timeline, when the samples were recollected, different problems appeared in the wastewater pilot plant, probably, affecting the composition of the AS causing it to behave different. In order to improve the operation of the SST and the quality of the effluent, these tests need to be repeated and more research need to be done for having more reliable data.

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